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Review

Review of bioplastics as food packaging materials

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Abstract: In this paper, food packaging materials and bioplastics applied as materials for food packaging are reviewed. Other possible materials, such as plastics, paper, metal, and glass, are also discussed. The advantages and disadvantages of every material are highlighted. The awareness of sustainability and the depletion of petroleum sources have contributed to the studies or innovations of using green materials, such as starch/polylactide, as food packaging. Bioplastic materials have several weaknesses in terms of their mechanical and barrier properties that have resulted in several studies on composite systems. These weaknesses have been reviewed and analyzed to determine the potential of bioplastic composites for application as food packaging materials.

Keywords: bioplastic; food packaging; plastic; composite; nanofiller

1. Introduction

1.1. Food packaging

Packaging can be defined as materials that are used to contain or temporarily contain, handle, protect, or transport articles and are generally disposed of as waste after usage [1]. In the food processing industry, packaging is a crucial process for preserving food quality and safety, providing food protection, presenting food, and preventing food degradation by physical, chemical, or biological contamination [2–5]. Kim et al. [6] also mentioned that food packaging that is successful in the market should have high quality and safety standards and should meet the requirements of governmental regulations and policies.

1.2. Food packaging characteristics

Different food packaging applications affect the selection of materials that are used as food packaging. The selection of food packaging materials highly depends on the nature of the food to be packed [6–7]. Paine & Paine [8] listed several vital factors that must be considered when selecting packaging materials. The guidelines proposed by Paine & Paine [8] for the food packaging designer or manufacturer to consider while selecting suitable materials for a product include packaging production methods, display requirements, economic considerations, marketing needs, specific product characteristics, and packaging material properties. Some food packaging materials have antimicrobial functions, good mechanical and thermal properties, suitable optical properties, ecofriendliness, and good barrier properties, including gas, vapor, and aroma barrier properties [9]. Figure 1 shows the general properties of food packaging materials.

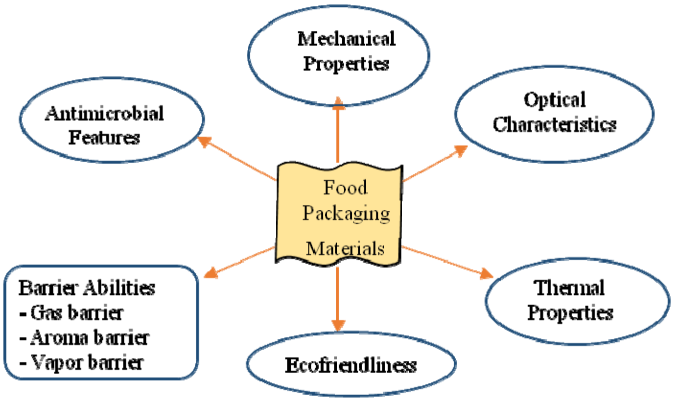


Figure 1. General properties of food packaging materials.

1.2.1. Barrier properties

The barrier properties of food packaging, including permeability by gas, water vapor, and aroma, are one of the most crucial properties for consideration in the selection of food packaging materials [10]. Given that food packaging acts as a protective layer for food, food packaging materials should at least have good resistance to gases and moisture from the environment [11]. The ultimate goal for food packaging is to maintain the quality of the food within the designed shelf-life by providing a sufficient barrier [12]. If the packaging lacks a good oxygen barrier or moisture barrier property, the food becomes rancid after oxidization and acquires an unpleasant smell or taste. Rancidity is caused by the oxidation of oils and fats through two main pathways: oxidation by oxygen and hydration by water [13,14]. Aroma is another basic element of food. Aroma scalping occurs if the packaging has a poor aroma barrier, in this case, either the food aroma diffuses out or is affected by aromas from the environment through the packaging materials and causes flavor changes [15,16].

Improvements in nanotechnology, especially in nanomaterials, can greatly improve the barrier properties of packaging materials [17]. The industrial application of nanocomposites has great potential to improve barrier properties because the production cost of nanocomposites is very low [18]. Sangroniz et al. [19] investigated packaging material exhibiting chemical recyclability while possessing the desired mechanical and barrier properties.

1.2.2. Antimicrobial properties

Food safety is a crucial issue and a basic human right [20]. If we ignore food safety and allow food to be spoiled by microorganisms or pathogens, it will be unsafe to consume and may cause illness if consumed [21]. Thus, food safety and food quality are issues of concern for consumers and food industries. These issues also reflect the need for an antimicrobial packaging system wherein an antimicrobial agent is incorporated into packaging materials or polymers to prevent microorganisms from contaminating food [22]. In general, an antimicrobial agent prolongs food preservation and makes food safe to consume by deteriorating the growth kinetics of microorganisms [23]. Some common antimicrobial nanocomposites are chitosan, silver nanoparticles, nanoclays, silica, titanium dioxide, zinc oxide, and copper [22,24].

1.3. Food packaging materials

Different types of packaging materials, namely, glass, metal, plastics, wood, and paper/paperboard, are available on the market [1,11]. The pros and cons of different food packaging materials are listed in Table 1.

Table 1. Pros and cons of different type of food packaging materials.

Type of materials	Pros	Cons	References
Glass	Recyclable Inert to a variety of foods	Heavy and fragile Expensive to transport	[25,26]
Metal	Long shelf life Resistant to heat	Expensive May be corroded	[27,28]
Plastic	Difficult to break Can be shaped into various forms	Poor heat resistance Nonbiodegradable	[25,29]
Wood	Sturdy Easy to repair	Only used as pallets and crates	[1]
Paper/paperboard	Easily printable surfaces Low cost Lightweight	Weak barrier against water Used for dry products only	[4,27]

2. Plastic packaging

Parkesine, a cellulose derivative invented by Alexander Parkes, is the first manmade plastic and was publically presented at the 1862 Great International Exhibition in London [6,30,31]. Since then, plastics have been developed and diversified [6]. The plastics that are used today are predominantly made from crude oil or natural gas and are also known as petroleum-based plastics [32]. Plastics are good choices for food packaging given their cheapness, easy processability, light weight, good resistance to oil and chemicals, excellent gas and water vapor barrier properties, and easily reusability and recyclability in terms of sustainability [1,3,5,6,33]. Some conventional petroleum or fossil-based plastics used in packaging include polypropylene (PP), polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polystyrene (PS), and other plastics, such as bioplastic polylactide (PLA) [1,33,34].

Polyethylene (PE) and PP are of the most common and generally used materials in food packaging because they possess excellent chemical and moisture resistance; moreover, they are easy to process and cheap [11,25,35]. PE consists of two basic categories, namely HDPE and LDPE, wherein HDPE plastics have numerous short side branches and a tightly packed structure, whereas LDPE have numerous long branches [25]. Although they are good chemical and moisture barriers, they are relatively permeable to oxygen and are thus poor odor barriers [36]. PE also has relatively lower heat resistance than other plastics, and PE films melt at relatively low temperatures [37].

PET is an emerging material that has been used in food packaging for the last several years [25,38] because it has higher heat resistance and mechanical strength than many plastics [37]. Moreover, it is an inert material that possesses good gas and moisture barrier properties and can be modified to present specific properties that are suitable for various packaging applications [11,38]. This characteristic makes PET a good option as a packaging material.

PLA is a promising biobased and biodegradable polymer that can be used as a food packaging material [33,39]. PLA is ideal for fresh organic packaging because it has good breathing properties [1]. However, pure PLA exhibits some limitations, such as water permeability, brittleness, and easy degradation under significant increases in temperature [1,39]. Compositing PLA with other components can confer PLA with increased tensile strength and water resistance, antimicrobial properties, and reduced processing costs [33,40,41].

However, these plastics are mostly nonbiodegradable, nonrenewable, and noncompostable, therefore causing major environmental and disposal issues worldwide [5]. They are the most challenging packaging materials to recycle [1]. Traditional plastics are so durable that they are not readily degraded in their ambient surroundings; they persist in the environment because polymers require numerous or even hundreds of years to decompose in the normal natural environment [42]. According to a report from the OECD Environment Directorate [32], over 60% of plastic waste comes from packaging. Singh et al. [42] stated that 90% of plastic solid wastes are recyclable, but 80% of them are sent to landfills, 8% are incinerated, and only 7% are recycled. The landfill disposal of HDPE also causes serious consequences because it produces greenhouse gases [42].

3. Bioplastic packaging

Food packaging should be natural and environmentally friendly [43]. Bioplastics or biopolymers from renewable resources have attracted growing interest from industries as a solution to the environmental problems and limited resources of petroleum-based polymers [2,33]. In 2018, the bioplastics used in the packaging market accounted for approximately 65% of the global bioplastic production [44]. Some currently produced and applied biopolymers based on renewable resources include PLA, cellulose, and starch, which are biopolymers that are directly obtained from argowastes [33]. However, “biobased” does not equal “biodegradable” or compostable [45–47]. Biobased products include raw materials that are renewable and can be replenished via natural processes [48]. Biodegradable products include polymers that can be degraded by microorganisms within a certain period of time in the environment [48]. Compostable bioplastics are a subset of biodegradable plastic. Therefore, all compostable bioplastics are biodegradable but not all biodegradable bioplastics are compostable [49]. Table 2 shows the different types of bioplastics found on the market.

Table 2. Types of bioplastics on the market.

Types of bioplastic	Properties	Examples	References
Polymers from biomass	Compostable	Starch-based, cellulose-based, protein-based	[50,51]
Polymers from bio-derived monomers	Biodegradable or recyclable	PLA, bio-based PE, bio-based PET, bio-based PP	[52–55]
Polymers from microbial fermentation	Biodegradable	Polyhydroxyalkanoates (PHA)	[56]
Polymers from both bio-derived monomers and petroleum-based monomers	Biodegradable or recyclable	poly(butylene succinate) (PBS), poly(trimethylene terephthalate) (PTT), Pro-oxidant Additive Containing (PAC) plastic	[53,57]

However, if used alone for packaging purposes, biopolymers or bioplastics show some limitations due to their poor water barrier properties, brittleness, high vapor permeability, and low heat deflection temperatures [3,5,6]. Thus, biopolymers are strengthened with nanofillers to enhance their mechanical properties, barrier properties, and heat [3,5]. Bioplastics also have some limitations in terms of production costs, functionality, and compatibility with other polymers in recycling streams [6,58].

3.1. Bioplastic reinforcement

As mentioned above, bioplastics alone have some limitations, including low water and chemical resistance, low heat resistance, and brittleness. The strength of bioplastics can be enhanced through several ways, including physical and chemical crosslinking. Some research has done on the physical treatments, including heat, dehydrothermal, and ultrasonic treatments, of protein-based bioplastics [59,60]. However, this review focuses on the reinforcement of bioplastics through chemical crosslinking. Several potential additives can be used as fillers for bioplastics: nanoclays, cellulose, silica, silver nanoparticles, and metal oxides (zinc, magnesium, and titanium oxides) [3,5]. These additives are in the micro- to nanosized form. Nanofillers can enhance the mechanical properties, barrier properties, and heat resistance of bioplastic nanocomposites compared with those of virgin bioplastics [3]. Chakravartula et al. [61] produced an edible composite film based on pectin/alginate/whey protein concentrate. Although nanofiller reinforcement can greatly improve bioplastic performance, we should not forget about the environmental and human health safety concerns posed by these nanomaterials during their application [62,63].

3.1.1. Nanoclays

Nanoclay or layered silicates are one of the most commonly used and researched agents for food packaging [5]. Nanoclays have the advantages of ubiquity in nature, easy processing, excellent performance, and cheapness [5,64]. Nanoclays have been successfully used as nanofillers in food packaging materials because they enhance the barrier properties of nanocomposites, improve mechanical properties and water resistance, decrease water vapor permeability, and confer flame retardance [64–66]. Mohanty & Swain [3] stated that nanoclay composites can be classified into three categories, namely intercalated, exfoliated, and tactoid. Exfoliated nanoclay has been proven to exhibit the best properties as the result of the optimal interaction between polymer and clay [3,5]. Montmorillonite is the most widely used nanoclay in food packaging because its high surface area and aspect ratio make it an excellent reinforcing filler [5,62].

3.1.2. Nanocellulose

Cellulose is among the most abundant polymers in nature that can readily be derived from available biomass [33,67]. Nanocellulose is also suitable for use in bioplastic reinforcement because cellulose can produce high strength-to-weight ratio nanomaterials and has an expected lower cost than other nanomaterials while also being biodegradable and environmentally friendly [5,67]. Farahhanim et al. [68] stated that cellulose has an encouraging prospect for enhancing the mechanical and thermal properties of polymers. Two main types of cellulose nanostructures can be applied as reinforcement in food packaging materials, namely, cellulose nanocrystals (CNCs) and nanofibers (CNFs) [5,69]. Xu et al. [70] reported that CNCs and CNFs can reinforce polymer nanocomposites and that CNFs possess higher strength and moduli than CNCs because of the more significant aspect ratio and fiber entanglement but reduced strain-at-failure shown by CNFs.

Bacterial cellulose (BC) is synthesized from microorganisms [69,71]. It has several advantages over plant-based cellulose, such as short harvest time, easy cultivation, and zero lignin and hemicellulose content [72–74]. Given these properties, BC is ecofriendly because it does not require harsh chemicals for purification [69]. Zhao et al. [71] stated that the main drawback of BC in industrial application is its high production cost because its yield is highly affected by medium content, culture condition, and bacteria used.

3.1.3. Silver nanoparticles and metal oxides

Silver nanoparticles are widely known for their antimicrobial properties, which they exert by degrading cell membranes and causing bacterial death [3,5]. Studies on applying silver nanoparticles in food packaging materials have found positive results for the inhibition of bacterial growth and the extension of food shelf-life [62,75,76]. Metal oxides, such as magnesium oxide [77,78], zinc oxide, and titanium dioxide, can act as antimicrobial agents when applied in food packaging materials [3,5,62,63]. These oxides also have been recognized by the U.S. Food and Drug Administration as safe for food application [62].

3.2. *Bioplastic composites*

3.2.1. PLA composite

PLA is a type of compostable and biocompatible thermoplastic originating from renewable resources, such as corn, sugarcane, and potato starch; it is widely used in packaging applications [1,2,47,79]. PLA is limited by its high brittleness, low deformation at peak, low melt strength, and weak gas barrier relative to polyolefin [2]. Thus, PLA must be modified to improve its properties. Several materials, such as plasticizers, polymers, nanoclays, carbon nanotubes, and starch, have been blended into PLA matrixes [2]. PLA is also frequently blended with other biobased and or biodegradable polymers, such as PHAs, to improve stiffness and strength and to reduce [47,80]. Genovese et al. [81] reported that polymers with triblock ABA architecture, wherein A is PLA and B is an ad hoc synthesized random biobased aliphatic copolyester poly(propylene/neopentyl glycol succinate), show improved mechanical and barrier properties. The B block facilitates composting. Figure 2 shows the general structure of PLA.

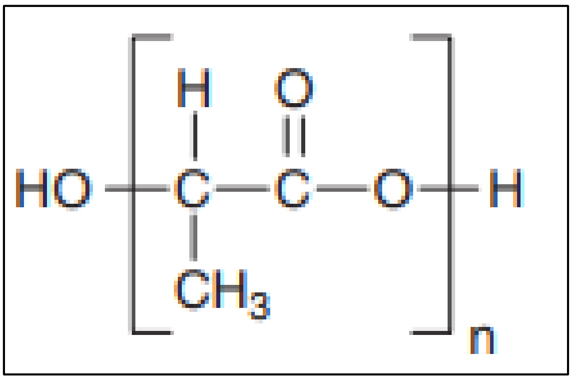


Figure 2. Structure of PLA.

3.2.2. Starch composite

Starch is one of the least expensive biomaterials [82]. It is also abundant, biodegradable, and renewable, and its possibility of blending with conventional polymers has garnered wide interest in the bioplastic market [2,33,83]. Blending starch with a nonbiodegradable plastic can also promote the biodegradability of the plastic [5,84]. Native starch lacks thermoplastic properties [83]. Thermoplastic starch (TPS) can be obtained through the addition of plasticizers under heating after starch destruction [2,5,83]. Starch is often used as a filler for other bioplastics to reduce production cost [2]. Blending with nanoclay improves the properties, including mechanical properties, thermal stability, and water resistance, of TPS [83]. Sun et al. [84] also discovered that starch films reinforced with calcium carbonate nanoparticles show significant improvements in tensile strength, elongation, and Young's modulus. Fibers can also enhance the mechanical properties, gas barrier properties, moisture resistance, and thermal stability of TPS [83,85]. Figure 3 shows the general structure of starch.

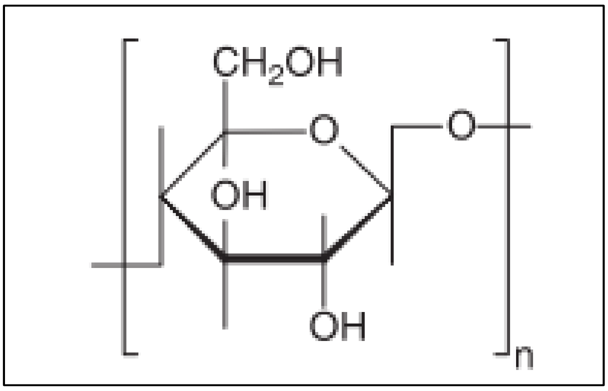


Figure 3. General structure of starch.

3.2.3. Polyhydroxyalkanoate composite

Polyhydroxyalkanoates (PHAs), which are environmentally friendly, biodegradable biobased polymers that can be produced via bacterial fermentation, have drawn considerable attention recently [86,87]. The properties of these biopolymers are very similar to those of traditional fossil fuel-based plastics, such as PP and PE; given these properties, PHAs have great commercial potential to replace conventional plastics [86,88,89]. However, PHAs face some drawbacks in commercial applications because they are brittle, thermosensitive, and ductile and possess limited processing malleability and poor gas barrier properties [90,91]. Mannina et al. [86] also reported that the production cost of PHAs is one of the most important factors to consider in the industrial production of PHAs for competition with conventional plastic. Various polymers and nanofillers, such as carbon nanotubes, nanoclays, cellulose, metal oxides, and bioactive glasses, are composited with PHAs to improve their performances significantly [9,90,91]. The most popular commercially applied PHA is poly(3-hydroxybutyrate), which is used in various industries as food packaging and films and in the medical field [48]. Figure 4 shows the general structure of PHA.

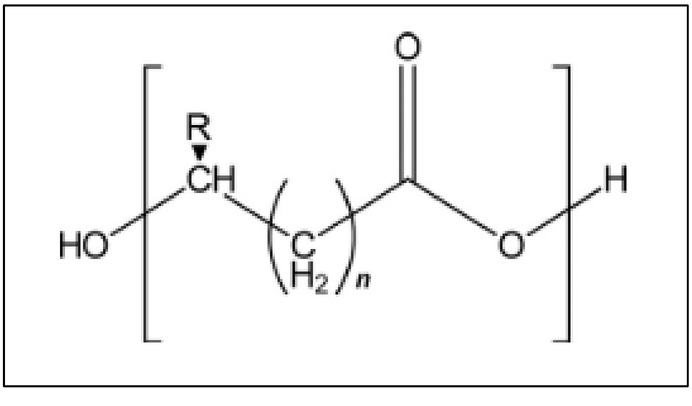


Figure 4. Structure of PHA.

3.2.4. Polybutylene succinate composite

Polybutylene succinate (PBS) is a biodegradable polymer that is produced through the condensation of succinic acid and 1,4-butanediol [92,93]. PBS has high crystallinity, great mechanical properties and thermal stability, and good dyeing properties and is thus suitable for processing through conventional methods, such as injection molding and extrusion [48,88]. These properties also make PBS a suitable replacement for HDPE and PP in various applications, such as housewares, agriculture, and packaging [88,94]. PBS has very good flexibility [2,94–96], and many studies have blended PLA and PBS to enhance their properties [95–99]. Soccio et al. [100] blended inedible wheat flour with various amounts of PBS-based green copolymer to obtain the polymer with the best mechanical performance. Quattrosoldi et al. [101] improved the thermal stability, flexibility, and compostability of PBS by adding different amounts of Pripol 1009. These studies showed that PBS has high potential for production as a packaging material if its physical properties undergo further improvement. Figure 5 shows the general structure of PBS.

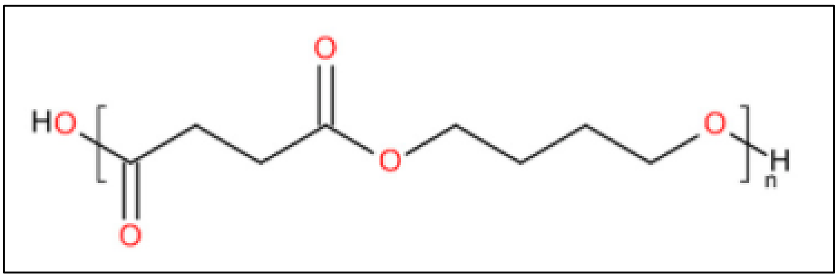


Figure 5. Structure of PBS.

3.2.5. Furandicarboxylic acid composite

Furandicarboxylic acid (FDCA) is a new emerging biobased polymer that has attracted considerable interest from the scientific and industrial fields [102]. It was identified by the US Department of Energy as a top value-added chemical derived from biomass [103]. FDCA can be synthesized via several methods, including oxidative production from biobased 5-hydroxymethylfurfural through electrochemical, catalytic, or noncatalytic and biocatalytic processes [104]. A completely biobased alternative to PET, namely poly(ethylene furanoate) (PEF), a composite produced from FDCA, has been recently developed [105]. Terzopoulou et al. [106] found that PEF can start undergoing commercialization in 2023 and will reach a market value of $129.3 million by 2025 given its similarity to PET. Guidotti et al. [107] also reported that biobased poly(pentamethylene furanoate), one of the composites produced from FDCA, has outstanding physical properties and excellent barrier and mechanical properties, which are the main factors for consideration when selecting packaging materials. However, the use of FDCA remains limited due to its high price and bottlenecked industrial production [108].

4. Plastic waste and recycling

A report on global plastic analysis by Geyer et al. [109] stated that the cumulative plastic waste produced from primary and recycled plastics in 1950–2015 reached 6300 million tons. According to the report, 60% of plastic wastes are sent to landfills, 12% are incinerated, and only 9% are recycled. The packaging industry accounted for the highest amount of plastic waste or 54% (141 million tons) of the plastic waste generated in 2015 [109].

Since the mass production of plastics began decades ago, most plastic products have been disposed of as trash [110]. "Our World in Data" also shows the fate of global plastic waste from 1950 to 2015. Recycling started increasing in 1988 when only 0.60% of plastic waste was recycled; in 2015, 19.50% of plastic waste was recycled [111]. Figure 6 shows the global share of plastic waste by disposal method.

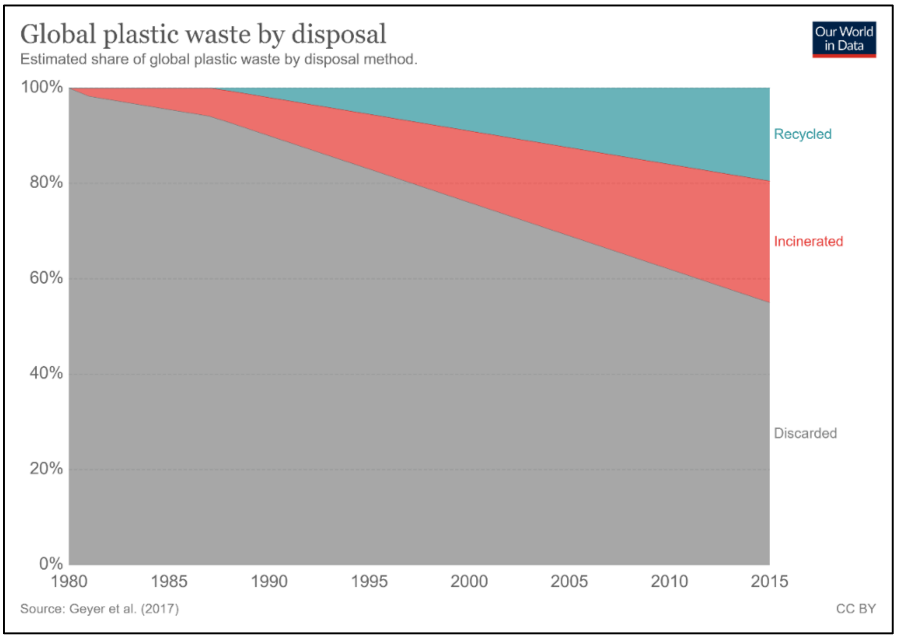


Figure 6. Global plastic waste by disposal method [111].

Although plastic waste is well known to be an emerging waste that can cause environmental pollution, the extent of this problem has yet to be realized. "The Star Online" reported that Malaysia is now one of the world's worst offenders in plastic pollution; in Malaysia, most plastics are simply dumped, a small portion is incinerated, and only 2% of plastic waste is recycled [112]. This scenario was exacerbated when Malaysia imported approximately half a million metric ton of plastic waste in the first half of 2018 [113]. A dataset in "Our Word in Data" showed that total plastic waste generation in Malaysia reached 2.03 million ton per year in 2010 and that 55% of the plastic waste was inadequately managed, accounting for 2.94% of the global mismanaged waste in 2010 [111]. Recently, some recycling factories in Malaysian cities have been found to operate illegally by burning plastic waste [114], and 139 plastic recycling factories all over Malaysia were shut down by the authorities in July 2019 [115]. Burning plastic causes air pollution, and the toxic fumes that are released from burning plastic pose a threat to human and animal health [116]. Other illegal plastic waste facilities in Malaysia use environmentally harmful techniques that may result in environmental impacts [113,117].

5. Future of bioplastics in food packaging

Based on the report "Biobased Building Blocks and Polymers—Global Capacities, Production and Trends 2018–2023" [118], the total production volume of bioplastics or biopolymers has reached 7.5 million tons, which account for 2% of the total production volume of petrochemical polymers. The report also stated that the production of biobased polymers will continuously increase with the expected CAGR of approximately 4% until 2023 and that its share in the total polymer and plastics market will remain constant at approximately 2% of the market. A report from European Bioplastics [119] further categorized bioplastics as biobased/nonbiodegradable and biodegradable. The total capacity of bioplastics in 2018 in this report is only 2.112 million tons, whereas that in the previous report is 7.5 million tons because European Bioplastics excluded polyurethane (PUR) given the absence of reliable data on the actual volumes of PUR [119].

Figure 7 depicts the global production capacities of bioplastics in 2018–2023. Figure 8 shows the global production capacities of bioplastics in 2018 by material type.

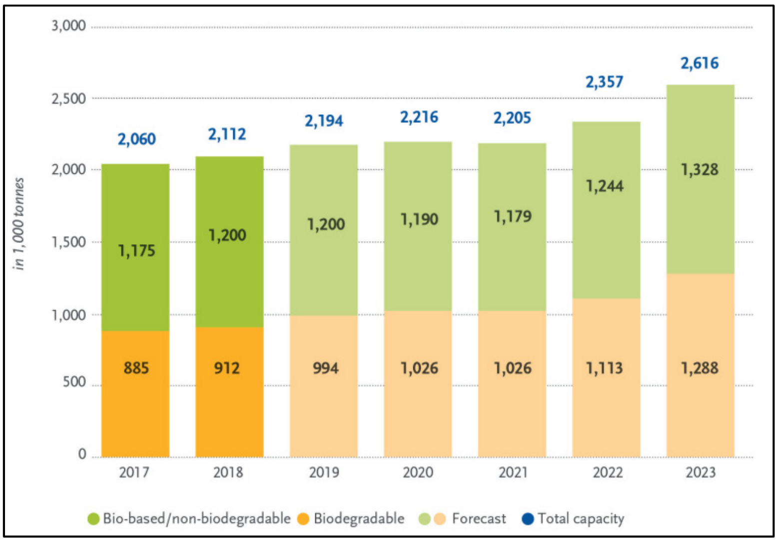
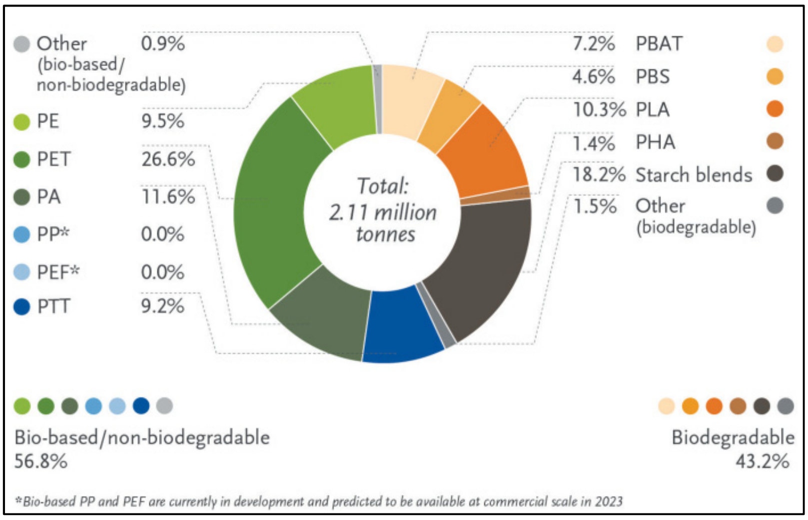


Figure 7. Global production capacities of bioplastics in 2018–2023 [119].



*Bio-based PP and PEF are currently in development and predicted to be available at commercial scale in 2023

Figure 8. Global production capacities of bioplastics in 2018 by material type [119].

Along with the rise of plastic use worldwide, the sustainability issue has attracted growing attention as the United Nations urged all the countries to achieve the 17 Sustainable Development Goals (SDGs). The 17 SDGs not only focus on development, but also people and environment. With the continuous increase in the global population, the agricultural sector has continued expanding and producing agricultural waste [120]. Those biomasses can be utilized and converted into resources, including bioplastics. Bioplastics are promising but are not the only solution to plastic pollution [121]. According to European Bioplastics [122], the current feedstock used to produce bioplastics relies on less than 0.02% of the global agricultural area. Several studies are investigating the use of using agricultural waste in the production of bioplastics [123–126].

6. Conclusions

Bioplastics have considerable potential as replacements of fossil-based plastics in many applications, such as food packaging. They have been applied in several food packaging industries. Molenveld et al. [1] reported that PLA and bio-PE are used as bottles to contain fruits, milk, and dairy products. PLA, starch blends, and cellophane are applied as films, trays/dishes, and containers to store food, such as fruit and vegetables, meats, fish, cheese, and eggs. Bioplastics can be used as single-use plastic materials. For example, Evoware, which produces seaweed-based packaging had produced edible grade-food wraps, coffee sachets, and dry seasoning sachets [127].

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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